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ABSTRACT

Winter wheat (*Triticum aestivum* L.) is grown on the Southern Great Plains under dryland conditions and under varying irrigation regimes. Relationships between water and fertilizer needs are not well defined. Field studies were conducted to determine: (i) the interacting effects of N fertilization and irrigation on N and P needs, wheat yields, and yield components; and (ii) the effects of timing of water deficit periods on N and P needs, wheat yields, and yield components. Studies were conducted on a Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll). Respective N and P rates ranged from 0 to 210 kg ha^{-1} and 0 to 40 kg ha^{-1}. Irrigations were applied or withheld to allow the crop to be nonstressed (I-1), stressed during heading and grain filling (I-2), stressed during tillering and jointing (I-3), and stressed throughout spring (I-4). Two-year average data showed that 140 kg N ha^{-1} was sufficient for maximum grain yields on treatment I-1, while 70 kg N ha^{-1} was sufficient on treatments on I-2 and I-3, and no N response occurred on treatment I-4. Compared to treatment I-1, grain yields were 27, 32, and 52% less on treatments I-3, I-2, and I-4, respectively. Water use efficiency (WUE) increased with increments of N through 140 kg ha^{-1} on treatment I-1, and through 70 kg ha^{-1} on treatments I-2, and I-3 but applied N did not affect WUE on treatment I-4. In 1981, WUE was highest on treatment I-1 and lowest on treatment I-4; in 1982, however, WUE was highest on treatment I-4 and lowest on treatments I-1 and I-3. For limited irrigation, irrigating during tillering and jointing would be preferable to allowing stress then, and irrigating during heading and grain filling, because there is still potential for high yields if precipitation occurs during heading and grain filling.

IN 1980 the area of winter wheat in the Texas High Plains was approximately 1 345 000 ha, 34% of which was irrigated. Amounts of irrigation applied ranged from very limited to adequate for maximum yields. Limited irrigation, i.e., applying less water than is required for potential evapotranspiration and maximum yield, is practiced on crops such as wheat, grain sorghum [*Sorghum bicolor* (L.) Moench] and cotton (*Gossypium hirsutum* L.) (Musick and Dusek, 1980). With significant seasonal rainfall, limited irrigation can increase water use efficiency of these crops (Schneider et al., 1969; Stewart et al., 1983). At present, available fertilizer recommendations are based on adequate water application. There is little information on which to base fertilizer recommendations for wheat grown under limited irrigation in this region. Also, currently, most producers plant semidwarf varieties with yield potentials near 7.0 Mg ha^{-1}. The taller types once used tended to lodge when grown with adequate water and fertilizer, and yields of 3.5 Mg ha^{-1} were near maximum.

Jensen and Sletten (1965) conducted a 3-yr irrigation-fertilizer study at Bushland using 'Concho' wheat, in which, with adequate water, yields increased linearly by 13.5 kg ha^{-1} for each kilogram of N applied up to 135 kg ha^{-1}. At rates of 200 kg N ha^{-1}, lodging occurred and yields were lower than those at the 135 kg N ha^{-1} rate. With limited irrigation (preplanting only or preplanting plus one 100-m irrigation in the spring), there were large year-to-year variations in yields due to variations in amount and distribution of precipitation. In a year with low March to May rainfall, N fertilizer did not affect yields, but in 2 yr with above-average March to May rainfall, responses were obtained from applied N up to 135 kg ha^{-1}. Phosphorus fertilizer did not affect yields. With optimum soil water, seasonal evapotranspiration averaged 711 mm.

Pope (1963) found that the most profitable N fertilizer rate for wheat on clay soils on the Texas High Plains averaged 90 kg ha^{-1}. At some locations the 135 kg ha^{-1} rate resulted in optimum yields, while at others, 45 kg ha^{-1} was sufficient. Pope (1963) emphasized the importance of soil tests in predicting fertilizer needs. Phosphorus did not affect yields on most clay soils, even though soil test P (NH_4O Ac-extractable) was low and was further reduced under intensive cropping.

Schneider et al. (1969) reported that the most critical period for adequate soil water for winter wheat was from the booting through grain filling stages. They found that timing of irrigation was as important as total quantity of water applied. Two or three well-timed spring irrigations produced yields approaching those produced at the optimum water level, but the water applied in one well-timed spring irrigation was

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Table 1. Dates of planting, irrigation, and harvest and amounts of water applied.

Treatment	Planting date	Fall irrigation		Early spring		Heading		Grain filling		Harvest date
		Date	Amount	Date	Amount	Date	Amount	Date	Amount	
			mm		mm		mm		mm	
					1980–1981					
I-1	15 Oct.	5 Nov.	102	17 Apr.	127	6 May	102	27 May	102	22 June
I-2	15 Oct.	5 Nov.	102	17 Apr.	127	–	–	–	–	22 June
I-3	15 Oct.	5 Nov.	102	–	–	6 May	152	27 May	102	22 June
I-4	15 Oct.	5 Nov.	102	–	–	–	–	–	–	22 June
					1981–1982					
I-1	29 Oct.	–	–	16 Apr.	127	14 May	127	11 June	127	6 July
I-2	29 Oct.	–	–	16 Apr.	127	–	-	–	–	6 July
I-3	29 Oct.	–	–	–	–	14 May	127	11 June	127	6 July
I-4	29 Oct.	–	–	–	–	–	–	–	–	6 July

used as efficiently as that applied in multiple irrigations.

The objectives of this study were to determine (i) the interacting effects of N fertilization and irrigation on wheat yields and yield components; and (ii) the effects of timing of water deficit periods on N and P needs, wheat yields, and yield components.

MATERIALS AND METHODS

The studies were conducted on Pullman clay loam at the USDA Conservation and Production Research Laboratory in Bushland, TX (35°12′ N, 102°5′ W), for 2 yr in level borders on a slightly sloping area (before leveling). The experiment was a randomized block, split plot design with three replications. Main plots, irrigation treatments, were 12 by 46 m in 1980 to 1981, and 12 by 37 m in 1981 to 1982. Subplots, fertilizer treatments, were 6 by 15 m and 6 by 12 m in the respective seasons. Fertilizer treatments were N at rates of 0, 70, 140, and 210 kg ha^{-1}, each in combination with 20 kg P ha^{-1}, and P rates of 0 and 40 kg ha^{-1} in combination with 210 kg N ha^{-1}. Irrigation variables were: I-1 (nonstressed), fall irrigation plus three spring irrigations; I-2 (stressed during heading and grain filling), fall irrigation plus one early spring irrigation; I-3 (stressed during tillering and jointing), fall irrigation plus two late spring irrigations; and I-4 (stressed throughout spring), fall irrigation only. Dates of irrigation are shown in Table 1. Planting dates were 15 Oct. 1980 and 29 Oct. 1981.

To remove accumulated residual N, the sites were cropped to irrigated wheat in the years immediately preceding initiation of the experiments. In both years 40 kg N ha^{-1} as NO_3 was present in the upper 1.8 m, and 18 kg $NaHCO_3$-extractable P ha^{-1} was present in the surface 0.15 m at planting time.

The N and P sources were ammonium nitrate (34–0–0)and concentrated superphosphate (0–46–0), respectively. The fertilizer was broadcast on the surface and tilled into the soil before planting each year. Winter wheat ('TAM 105') was planted at 50 kg ha^{-1}. In 1980, a fall irrigation was applied on 5 November; but in 1981, summer and fall rainfall had wet the soil and no fall irrigation was required.

Grain yields were measured by a plot combine, harvesting 1.5-m-wide strips from each subplot. Lengths of strips were 12 and 9 m in 1981 and 1982, respectively. Straw yields were obtained from single square meter samples from each subplot. Samples were threshed with a nursery thresher, and straw yield was determined as the difference between aerial dry matter and grain yield. Subsamples of grain and straw were oven-dried at 60°C, ground in a Wiley mill, and analyzed for total N by the method of Thomas et al. (1967). Grain protein concentration was calculated by multiplying grain N concentration by 5.7. Harvest indexes (HI) [wt. of grain/(wt. of grain + straw)] were calculated using yield from the square meter samples. The number of heads per square meter was the number of heads in the square meter samples. Grain samples for seed weight determinations were oven-dried at 60°C, counted with an electronic seed counter, and weighed. The number of seeds per square meter was calculated from grain yields and seed weights.

Soil water was measured by the neutron method. Two access tubes were installed in each main plot (one each in the 0 N + 20 P and 210 N + 20 P fertilizer treatments) after planting each year. Measurements were taken to 1.8-m depths by 0.30-m increments in 1980 to 1981, and by 0.20-m increments in 1981 to 1982. Measurements were made after planting, before each irrigation, at harvest, and at other selected times during the growing period. Water use was determined by summing precipitation, applied irrigation water, and the difference in soil water content (to the 1.8-m depth) between the initial and final measurements. The emergence irrigation (1980) was not included in the water use calculations because a plant stand had not been obtained. Initial soil water measurements were made after that irrigation.

Water use efficiency (WUE) in grain production was determined by dividing grain yields (130 g H_2O kg^{-1}) by cubic meters of water used. For the 0 N + 20 P fertilizer treatment, soil water use was determined using readings from that treatment. For the other fertilizer treatments, soil water use was determined using readings from the 210 N + 20 P fertilizer treatment. Irrigation water use efficiency (IWUE) was determined by dividing the increase in grain yield from an irrigation treatment by cubic meters of irrigation water applied.

Residual NO_3^--N was measured in the upper 1.8 m of soil after harvest each year. Samples were taken at 0.3-m depth increments from three locations per fertilizer plot and composited by depth increments. Nitrate-N was extracted by 0.1 *M* KCl and determined with an autoanalyzer (Kamphake et al., 1967).

Data were analyzed by analyses of variance (SAS Institute, 1982). When significant differences were found ($P = 0.05$), least significant differences (LSDs) were calculated.

RESULTS

Temperature and precipitation for each growing season are given in Table 2. In the 1980 to 1981 season, fall and winter temperatures were below average and spring temperatures were near average. After an emergence irrigation in the fall and above-average winter precipitation, the first spring irrigation was not applied until 17 April. Treatment I-1 was irrigated again on 6 May and 27 May. The 27 May irrigation may not have been required for maximum yields. A total of 53 mm of precipitation occurred after that irrigation and before harvest on 22 June.

Table 2. Summary of October to June precipitation and temperature data† for 1980 to 1982 at the USDA Conservation and Production Research Laboratory, Bushland, TX.

	October	November	December	January	February	March	April	May	June
				1980–1981					
Precipitation, mm	25	13	66	13	31	45	12	53	92
Temperature—Max., °C	21.9	12.9	13.2	11.6	14.1	15.1	23.6	25.4	32.3
—Min., °C	4.4	−1.9	−3.4	−5.4	−5.3	0.8	6.7	9.3	16.1
				1981–1982					
Precipitation, mm	52	37	0	1	5	8	22	47	108
Temperature—Max., °C	19.6	16.2	12.0	10.8	7.5	15.7	20.1	24.4	27.9
—Min., °C	6.7	1.5	−4.1	−7.2	−6.6	−1.2	3.0	9.2	13.1
				1938–1982 Avg.					
Precipitation, mm	41	19	13	11	12	19	28	69	75
Temperature—Max., °C	23.0	15.6	11.4	9.9	12.4	16.7	22.0	26.2	31.0
—Min., °C	6.1	−0.7	−4.6	−6.4	−4.3	−1.1	4.3	9.6	14.9

† Average of daily maximum and minimum temperatures for the months indicated.

In the 1981 to 1982 season, fall temperatures were near normal, but those from February through June were below normal. Fall precipitation was above normal; hence, no fall irrigation was applied. But precipitation was much below normal from December through April. The first irrigation was applied on 16 April. Treatment I-1 was irrigated again on 14 May and 11 June. The 11 June irrigation probably was not required for maximum yields, since a total of 135 mm of precipitation occurred between the last irrigation and harvest.

In both seasons, treatments I-1 and I-2 (previous to the stress period) were irrigated when soil in the root zone (to the 1.8-m depth in spring) was depleted to about 55% of plant available water. On treatment I-3, the soil in the root zone was depleted to about 40% of plant water when stress was terminated by irrigation.

Grain yields, straw yields, harvest indexes, heads per square meter, seeds per square meter, seed weights, N uptake by aerial parts at harvest, grain protein concentration, residual NO_3^--N, water use, WUE, and IWUE are presented in Tables 3 through 6.

Due to the interaction effects, the average data (of fertilizer treatments within water treatments) have little meaning. Hence, unless specific fertilizer treatments are mentioned, data for the 140 kg N + 20 kg P fertilizer treatment will be used in discussing the effects of water treatments.

Grain Yields. Maximum or near maximum yields were obtained on the I-1 treatment with 140 kg N ha^{-1} (Table 3, Fig. 1). With the I-3 treatment, yields still increased with increasing increments of N through 140 kg ha^{-1}, but the average increase from the second 70-kg increment of N was only 0.29 Mg ha^{-1}, while that from the second increment on treatment I-1 was 1.00 Mg ha^{-1}. Seventy kilograms of N ha^{-1} was adequate for near maximum grain yields with the I-2 treatment. For the I-4 treatment, water became more limiting than fertility, and there was no yield response to applied N. The N response data may be used in determining N fertilizer rates for specific yield goals. On treatment I-1, the ratio of available N at planting to grain produced was 1 to 32.5 (2-yr data, treatment I-1, 40 kg soil N + 140 kg fertilizer N ha^{-1}. Hence, in fertilizing for a given yield level, 1 kg N (fertilizer + soil N) would be required for each 32.5 kg of anticipated grain yield.

Applied P did not increase yields significantly; but on treatment I-1, the 210 N + 40 P treatment yielded 17% more than the 210 N + 0 P treatment (1981, 16%; 1982, 18%). On the other irrigation treatments, yields were lower than those on treatment I-1, and responses to P were not indicated. In 1981, yields on treatments I-3, I-2, and I-4 were 29, 35, and 63% lower, respectively, than those on treatment I-1. In 1982, the respective treatments yielded 25, 30, and 41% lower than treatment I-1.

Table 3. Grain yields, straw yields, and harvest indexes as affected by fertilizer and irrigation treatments.

Fertilizer treatment		Grain yield						Straw yield						Harvest index‡					
		Irrigation treatment					LSD	Irrigation treatment					LSD	Irrigation treatment					LSD
N†	P	I-1	I-2	I-3	I-4	Avg.	(0.05)	I-1	I-2	I-3	I-4	Avg.	(0.05)	I-1	I-2	I-3	I-4	Avg.	(0.05)
— kg ha^{-1} —		Mg ha^{-1}												grain yield/biomass yield					
								1981											
0	20	3.11	2.89	2.82	2.20	2.76	0.40	3.57	3.33	2.92	2.55	3.09	NS	0.434	0.466	0.467	0.455	0.456	NS
70	20	5.34	3.90	4.27	2.57	4.02	1.02	5.24	5.15	4.98	3.50	4.72	0.80	0.426	0.421	0.454	0.409	0.428	NS
140	20	6.23	4.08	4.44	2.33	4.27	0.52	6.92	5.50	4.64	3.90	5.24	1.92	0.434	0.417	0.467	0.413	0.433	NS
210	20	5.93	3.99	3.87	2.39	4.05	0.84	7.45	6.48	4.71	4.00	5.66	0.72	0.415	0.362	0.465	0.358	0.400	0.062
210	0	5.44	3.91	4.43	2.80	4.15	1.02	7.17	5.75	5.18	3.58	5.42	1.28	0.423	0.392	0.455	0.403	0.418	NS
210	40	6.29	3.94	3.95	2.54	4.18	0.43	7.20	5.86	4.66	3.77	5.37	1.76	0.434	0.409	0.468	0.383	0.424	0.054
Avg.		5.39	3.79	3.97	2.47			6.26	5.35	4.52	3.55			0.428	0.411	0.463	0.404		
LSD (0.05)		0.78	0.38	0.65	NS			1.67	1.12	0.77	0.60			NS	0.048	NS	0.048		
								1982											
0	20	2.80	2.66	2.56	2.94	2.74	NS	2.48	3.69	2.79	3.31	3.07	NS	0.455	0.469	0.502	0.477	0.476	NS
70	20	4.23	4.13	3.59	3.31	3.82	NS	5.99	5.74	4.15	4.49	5.09	NS	0.442	0.426	0.462	0.477	0.452	NS
140	20	5.34	3.74	3.99	3.16	4.06	0.93	5.81	5.33	3.90	4.04	4.77	NS	0.449	0.407	0.492	0.477	0.456	0.012
210	20	5.29	3.95	4.03	3.52	4.20	0.63	6.83	6.51	4.13	4.32	5.45	1.43	0.418	0.405	0.494	0.463	0.445	0.034
210	0	4.78	3.90	3.96	3.66	4.08	NS	5.55	5.70	4.42	3.99	4.92	0.98	0.459	0.408	0.471	0.458	0.449	NS
210	40	5.65	4.12	4.31	3.95	4.51	1.20	6.78	6.63	3.95	4.28	5.41	0.87	0.415	0.419	0.491	0.472	0.449	0.036
Avg.		4.68	3.75	3.74	3.42			5.57	5.60	3.89	4.07			0.440	0.422	0.485	0.471		
LSD (0.05)		0.81	0.61	0.57	0.79			0.77	NS	0.87	0.72			NS	0.042	NS	NS		

† The soil contained 40 kg NO_3^--N in the 1.8-m profile at planting; thus, available N = 40 kg soil N + fertilizer N.
‡ HI calculated using yield from square-meter samples.

Table 4. Head population m^{-2}, seed population m^{-2}, and seed weight as affected by fertilizer and irrigation treatments.

Fertilizer treatment		Heads						Seeds						Seed weight					
		Irrigation treatment					LSD	Irrigation treatment					LSD	Irrigation treatment					LSD
N†	P	I-1	I-2	I-3	I-4	Avg.	(0.05)	I-1	I-2	I-3	I-4	Avg.	(0.05)	I-1	I-2	I-3	I-4	Avg.	(0.05)
— kg ha^{-1} —		no. m^{-2}						no. m^{-2}						mg					
								1981											
0	20	382	379	323	368	363	NS	9 090	9 340	8 380	8 410	8 810	NS	34.2	31.5	33.8	26.2	31.4	NS
70	20	440	426	505	417	447	NS	15 360	12 110	12 670	10 480	12 660	2 710	35.0	32.2	33.7	24.7	31.4	NS
140	20	533	531	462	474	500	NS	18 690	14 100	14 090	9 440	14 080	2 740	33.4	29.1	31.6	24.8	29.7	5.2
210	20	518	652	477	449	524	102	18 620	15 860	11 740	10 660	14 220	5 510	32.1	25.5	33.1	23.0	28.4	7.3
210	0	504	529	549	449	508	NS	17 440	15 590	13 090	12 470	14 650	NS	31.7	25.7	31.7	22.9	28.0	7.1
210	40	516	504	530	458	502	NS	19 500	15 260	13 520	10 240	14 630	4 970	32.4	26.0	29.8	26.4	28.7	NS
Avg.		482	504	474	436			16 450	13 710	12 250	10 280			33.1	28.3	32.3	24.7		
LSD (0.05)		NS	107	NS	NS			4 440	3 350	2 150	3 450			NS	NS	NS	NS		
								1982											
0	20	256	348	291	345	310	NS	10 040	10 640	9 570	10 060	7 830	NS	27.8	25.0	27.0	28.9	27.2	NS
70	20	443	492	420	449	451	NS	15 390	16 420	12 560	11 930	14 080	4 000	27.8	25.1	28.6	27.7	27.2	2.1
140	20	439	561	368	403	443	117	21 210	17 870	13 630	11 730	16 140	3 180	25.2	21.0	28.9	27.0	25.5	2.4
210	20	461	552	404	437	464	NS	22 150	18 620	13 670	13 130	16 890	3 530	23.9	21.3	29.5	27.3	25.5	3.9
210	0	368	441	387	399	399	NS	20 070	19 770	13 970	13 300	16 780	4 210	23.8	19.7	28.2	27.7	24.9	2.8
210	40	489	504	409	381	446	NS	24 120	19 670	14 420	16 000	18 550	4 470	23.5	20.9	29.8	24.6	24.7	2.6
Avg.		409	483	380	402			18 830	17 170	15 560	12 690			25.3	22.2	28.7	27.2		
LSD (0.05)		101	NS	NS	NS			3 440	2 370	2 030	3 990			2.5	2.7	NS	NS		

† The soil contained 40 kg NO_3^--N in the 1.8-m profile at planting; thus, available N = 40 kg soil N + fertilizer N.

Straw Yields. On treatments I-1 and I-2, straw yields increased with increasing increments of N through 210 kg ha^{-1} in both years (Table 3). With the I-3 treatment, straw yields increased with the first 70 kg ha^{-1} increment of N then leveled off. On Treatment I-4, the first increment of N increased straw yields about 1 Mg ha^{-1}, but further increments of N had little effect. Applied P did not affect straw yields.

Treatment I-3 had similar effects on straw yields in the 2 yr, with yields being 33% lower than those on treatment I-1 in both years. Straw yields on treatment I-2 were 20 and 8% lower than those on treatment I-1 in 1981 and 1982, respectively. On treatment I-4, they were 44 and 30% lower than those on treatment I-1 in the respective years.

Harvest Index. Applied N did not affect HI on treatments on I-1 and I-3, but reduced them on treatment I-4 in 1981, and on treatment I-2 in both years (Table 3). Inspection reduced them on treatment I-4 in 1981, and on treatment I-2 in both years (Table 3). Inspection of the effects of irrigation treatments on HI shows that compared to those on treatment I-1, HI was decreased on treatment I-2 and increased on treatment I-3. These differences from treatment I-1 resulted in significant differences in HI between treatments I-2 and I-3, even when HI of both was not different from that of treatment I-1. In 1981, HI of treatment I-4 was not different from that of treatment I-1; but in 1982, HI was higher for treatment I-4 compared to treatment I-1. Stress during heading and ripening (I-2) reduced HI by reducing grain yields after most of the vegetative growth had been completed. The stress-induced premature ripening caused grain yield reductions by reducing both seed numbers and seed weights (Table 4). Stress during vegetative growth terminating at heading (I-3) reduced both straw and grain yields, but straw yields were reduced more than grain yields. On treatment I-3, water stress had little effect on head numbers, but seed numbers were reduced, indicating reduced head size. Since treatment I-3 was not water-stressed during seed filling, seeds filled normally and seed weights were not affected by stress. The significantly higher HI on treatment I-4 compared to treatment I-1 in 1982 resulted from the HI on treatment I-4 being unaffected by N applications, while there was a trend toward reduced HI with increasing N applications on treatment I-1 (Table 3).

Head Population. Head numbers were increased by applied N on treatment I-2 in 1981 and on treatment I-1 in 1982 (Table 4). In 1981, head numbers were increased by increasing increments of N through 210 kg ha^{-1}; and in 1982, they increased with increasing N rates through 70 kg ha^{-1}.

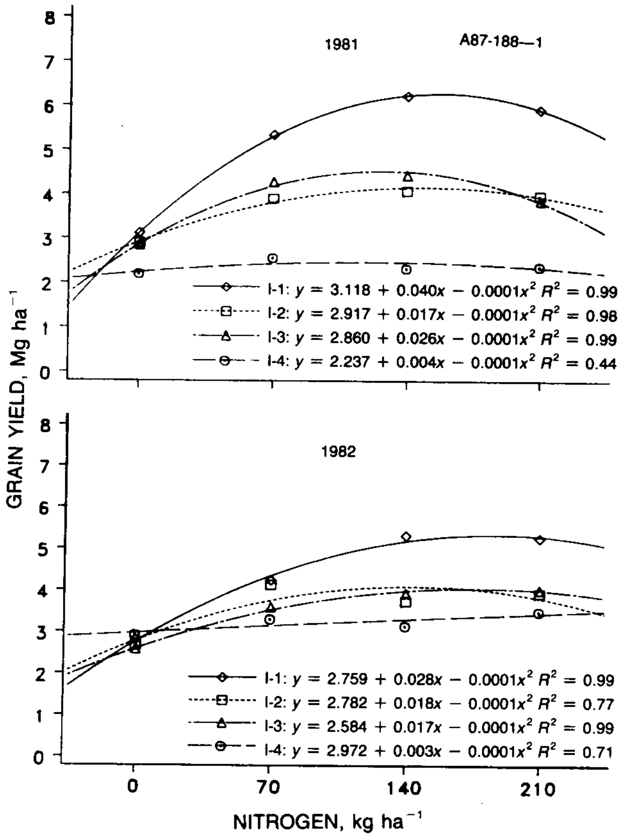

Fig. 1. Grain yields as affected by N fertilization and irrigation. I-1 = nonstressed, I-2 = stressed during heading and grain filling, I-3 = stressed during tillering and jointing, and I-4 = stressed throughout spring.

Limiting irrigation had little effect on the number of heads. In 1981 with the 210 N + 20 P treatment, and in 1982 with the 140 N + 20 P treatment, treatment I-2 had significantly more heads per square meter than the other three irrigation

Table 5. Nitrogen yields in aerial portion of plants, grain protein concentration, and residual NO_3^--N as affected by fertilizer and irrigation treatments.

Fertilizer treatment		N uptake						Grain protein‡						Residual NO_3^--N					
		Irrigation treatment					LSD	Irrigation treatment					LSD	Irrigation treatment					LSD
N†	P	I-1	I-2	I-3	I-4	Avg.	(0.05)	I-1	I-2	I-3	I-4	Avg.	(0.05)	I-1	I-2	I-3	I-4	Avg.	(0.05)
		kg ha^{-1}						g kg^{-1}						kg ha^{-1}					
								1981											
0	20	68.1	59.6	66.6	48.1	60.6	10.1	102	98	114	102	104	9	40	40	61	38	45	14
70	20	115.8	92.4	109.1	72.1	97.4	24.6	107	111	118	126	116	NS	52	57	55	54	55	NS
140	20	168.9	111.8	137.5	84.2	125.6	15.8	128	131	143	159	140	21	40	69	63	72	61	NS
210	20	173.3	124.5	129.7	91.1	129.7	18.0	141	147	149	162	150	NS	43	56	79	97	69	NS
210	0	161.5	123.4	137.5	92.4	128.7	32.0	144	143	138	152	144	NS	42	85	68	120	79	47
210	40	177.4	131.3	139.0	98.1	136.5	14.3	134	153	157	162	152	13	36	76	51	76	60	30
Avg.		144.2	107.2	119.9	81.0			126	131	137	144			42	64	63	76		
LSD (0.05)		20.2	13.2	22.3	13.8			14	21	20	15			NS	NS	NS	42		
								1982											
0	20	61.9	66.3	64.7	72.3	66.3	NS	107	110	117	115	112	NS	13	10	11	16	13	NS
70	20	109.8	105.2	106.3	98.7	105.0	NS	118	115	135	133	125	14	11	13	16	23	16	NS
140	20	139.2	114.7	126.1	104.7	121.2	NS	127	143	150	145	141	NS	21	25	29	69	36	NS
210	20	175.9	162.8	139.7	125.9	151.1	19.6	152	173	156	159	160	NS	77	73	85	99	84	NS
210	0	153.7	148.8	135.5	121.9	140.0	21.8	151	176	148	161	159	NS	112	62	54	162	98	NS
210	40	190.6	150.7	145.4	138.2	156.2	29.1	150	162	159	162	158	NS	72	77	96	125	93	51
Avg.		138.5	124.8	119.6	110.3			134	147	144	146			51	43	49	82		
LSD (0.05)		22.5	27.5	18.1	17.2			19	22	17	13			72	23	38	52		

† The soil contained 40 kg NO_3^--N in the 1.8-m profile at planting; thus, available N = 40 kg soil N + fertilizer N.
‡ Kjedahl N × 5.7.

treatments. The result in 1981 is not consistent with trends on the other fertilizer treatments. But in 1982 there were trends toward more heads on treatment I-2 than on the other irrigation treatments (on all fertilizer treatments). Logically, treatments I-1 and I-2 would have similar numbers of heads, and treatments I-3 and I-4 would have reduced numbers of heads due to plants being stressed during tillering. The reasons for the higher numbers of heads on treatment I-2 are not known.

Number of Seeds per Square Meter. The effects of N on seed numbers were similar in the 2 yr (Table 4). Seed numbers increased with increasing increments of N through 140 kg ha^{-1} on treatments I-1, I-2, and I-3. On treatment I-4, fertilizer effects on seed numbers were erratic. The only fertilizer treatments with significantly more seeds than the 0 N + 20 P treatment were the 210 N + 0 P treatment in 1981, and the 210 N + 40 P treatment in 1982.

On the adequately fertilized treatments, all limited irrigation treatments reduced seed numbers in both years. The reduction from treatment I-2 was less than that from the other two limited irrigation treatments except on the 70 N and 140 N treatments in 1981, when reductions were similar on treatments I-2 and I-3. Except on those two fertilizer treatments, there were trends towards fewer seeds per square meter on treatment I-3 than on treatment I-2, with reductions being greater in 1982 than in 1981. There were also trends towards fewer seeds per square meter on treatment I-4 than on treatment I-3, but differences were not as marked as those between treatments I-2 and I-3.

Reductions in seed numbers on treatment I-3 apparently resulted from reduced head size, since there was little effect on head population. Frank et al. (1987) found that the number of spikelets per spike was reduced by water stress during development of the juvenile inflorescence. On treatment I-2, head size and numbers of fertile florets would have been determined before the onset of water stress. Hence, reductions in seed numbers probably resulted from light-weight seeds being lost in threshing, or failure of fertilization of some of the florets.

Seed Weight. Fertilizer treatments had only minor effects on seed weights (Table 4). There were no significant differences in 1981, and in 1982 the only significant effects were on treatments I-1 and I-2, where seed weights were decreased with increasing increments of N through 140 kg ha^{-1}.

In 1981 the significant differences in seed weight among irrigation treatments resulted from reduction in weights on treatment I-4 compared to treatment I-1. Weights on treatment I-2 tended to be lower than those on treatment I-1 but were not significantly lower on any fertilizer treatment. In 1982, significant differences in seed weight resulted both from seed weights being reduced on treatment I-2 and increased on treatment I-3. Compared with those on treatment I-1, seed weights were significantly reduced by treatment I-2 for all fertilizer treatments except 0 N and 210 N, and significantly increased by treatment I-3 for all fertilizer treatments except 0 N and 70 N.

The decrease in seed weight with N fertilization on I-1 in 1982 and the trend toward a similar effect in 1981 cannot be attributed to water deficits during the ripening period. The smaller seeds may have resulted from the retention of more apical seeds in each spikelet, from insufficient photosynthetic surfaces for filling seeds to maximum size, or from a combination of both factors. Shimshi and Kafkafi (1978) stated that N may influence the relation between number of seeds and seed weight through (i) stimulating the retention of the more apical seeds in each spikelet, in addition to the basal seeds (since the former are inherently smaller, the average weight of the seeds is reduced), or (ii) stimulating the simultaneous development of more seeds per spikelet, more spikelets per head, or more fertile tillers per plant, thereby creating more competing sinks for photosynthesis, resulting in a reduction in weight of all the kernels. High temperatures shorten the grain filling period (Sofield et al., 1977); thus, high temperatures would enhance the effects of insufficient photosynthetic surface.

Reductions in seed weight on treatments I-2 and I-4 in 1981 and on treatment I-2 in 1982 resulted from shortening of the ripening period. Grains were shriveled, and test weights (data not shown) were reduced on those treatments. The reasons for seed weights on treatments I-4 being unaffected while they were reduced on treatment I-2 (1982 data) are not known.

Nitrogen Uptake. Nitrogen uptake (in straw plus grain at harvest) increased with increasing increments of applied N through 140 kg ha^{-1} in 1981 (Table 5). There were trends toward greater N uptake from the 210 kg N ha^{-1} treatment, especially on treatment I-1, but in no case was uptake from that treatment significantly greater than that from the 140

Table 6. Water use, water use efficiency, and irrigation water use efficiency as affected by fertilizer and irrigation treatments.

Fertilizer treatment		Water use				Water use efficiency						Irrigation water use efficiency				
		Irrigation treatment				Irrigation treatment					LSD	Irrigation treatment				LSD
N†	P	I-1	I-2	I-3	I-4	I-1	I-2	I-3	I-4	Avg.	(0.05)	I-1	I-2	I-3	Avg.	(0.05)
kg ha^{-1}		mm				kg grain m^{-3}										
								1981								
0	20	562	446	503	364	0.56	0.65	0.56	0.61	0.60	NS	0.28	0.55	0.25	0.36	NS
70	20					0.85	0.76	0.76	0.64	0.75	NS	0.84	1.05	0.68	0.86	NS
140	20					0.99	0.80	0.79	0.59	0.79	0.10	1.18	1.38	0.83	1.13	0.27
210	20	631	509	561	400	0.94	0.78	0.69	0.60	0.75	0.20	1.07	1.26	0.58	0.97	0.45
210	0					0.86	0.77	0.79	0.70	0.78	NS	0.80	0.87	0.64	0.77	NS
210	40					1.00	0.77	0.71	0.63	0.78	0.12	1.14	1.10	0.56	0.93	0.22
Avg.						0.87	0.76	0.72	0.63			0.89	1.04	0.59		
LSD (0.05)						0.12	0.09	0.13	NS			0.27	0.41	0.26		
								1982								
0	20	620	390	515	281	0.45	0.68	0.50	1.04	0.67	0.18	−0.03	−0.20	−0.14	−0.12	NS
70	20					0.67	1.03	0.70	1.21	0.90	0.28	0.25	0.65	0.11	0.34	0.27
140	20					0.92	0.93	0.77	1.15	0.94	NS	0.59	0.46	0.31	0.45	NS
210	20	634	403	515	274	0.83	0.98	0.78	1.29	0.97	0.13	0.47	0.33	0.20	0.33	NS
210	0					0.76	0.97	0.77	1.34	0.96	0.36	0.30	0.18	0.11	0.20	NS
210	40					0.89	1.02	0.84	1.44	1.05	0.31	0.46	0.39	0.14	0.33	NS
Avg.						0.75	0.94	0.73	1.25			0.34	0.30	0.12		
LSD (0.05)						0.13	0.15	0.12	0.29			0.25	0.84	0.44		

† The soil contained 40 kg NO_3^--N in the 1.8-m profile at planting; thus, available N = 40 kg soil N + fertilizer N.

kg N ha^{-1} treatment. In 1982, however, N uptake increased with increasing increments of applied N through 210 kg ha^{-1} on treatments I-1 and I-2, and through 140 kg N ha^{-1} on treatments I-3 and I-4. Applied P did not significantly affect N uptake.

On the unfertilized treatments, average uptake of N was about 60 kg ha^{-1}, indicating that the soil supplied that quantity of N through mineralization of organic matter, recycling of N in crop residues, etc. With adequate irrigation and approximately 200 kg N ha^{-1} (60 kg ha^{-1} from the soil and 140 kg ha^{-1} of applied N), maximum yields were obtained (5.8 Mg ha^{-1}), with N uptake of 154 kg ha^{-1}. About 68% of the 140 kg N ha^{-1} was removed by the plants. At the 210 kg N ha^{-1} rate, the proportion of applied N taken up dropped to 55%. On treatments I-2 and I-3, near-maximum yields (4.0 Mg ha^{-1}) were obtained with 70 kg ha^{-1} of applied N. Nitrogen uptake was 103 kg ha^{-1}, and the proportion of applied N taken up was 61%. At the 140 kg N ha^{-1} rate, the proportion of applied N taken up fell to 45%. On treatment I-4, the 60 kg N ha^{-1} supplied by the soil was adequate for yields as high as the water supply allowed (2–3 Mg ha^{-1}). Nitrogen applied on treatment I-4 increased N uptake without affecting grain yield. The increased N uptake was reflected in increased N concentration in grain and straw and some increase in straw yields.

Grain Protein. Grain protein concentrations increased with increasing increments of applied N on all treatments except treatment I-1 in 1981 (Table 5). On treatment I-2, protein increases continued through the 210 kg N ha^{-1} rate, and on the other treatments they continued through the 140 kg N ha^{-1} rate. In 1982, grain protein concentration was increased by increasing increments of N through 210 kg ha^{-1} on all except treatment I-3, where the 140 kg N ha^{-1} rate gave grain protein levels equivalent to the 210 kg N ha^{-1} rate. Applied P did not affect protein concentration of the grain.

In 1981, within fertilizer treatments, grain protein levels tended to be low on treatment I-1, where grain yields were highest, intermediate on treatments I-2 and I-3, where grain yields were somewhat limited by water deficits, and usually highest on treatment I-4, where water deficits were greatest. Differences in grain protein between water treatments tended to be greatest at intermediate N levels, where, with adequate water, most of the applied N was used in increasing yields without substantially increasing grain in protein, and, with limited water, yield increases were limited and more N was used in increasing grain protein. In 1982, grain protein concentrations on two of the 210 N fertilizer treatments on the I-2 irrigation treatment tended to be higher (though not significantly so) than those treatments on I-3 and I-4. This probably resulted from plants on those fertilizer treatments being under much water stress during late grain filling, resulting in shriveling of the grain. Test weight and seed weight data (Table 3) support this observation.

Residual Nitrogen in Soil. In 1981, N accumulated from the 140 and 210 kg ha^{-1} fertilizer N rates on treatment I-4, but there were no significant differences due to N rates on the other irrigation treatments (Table 5). On the other irrigation treatments, most of the applied N through the 210 kg ha^{-1} rate was apparently utilized by plants, remained in the soil in forms other than NO_3, or was lost in some manner. In 1982 there were significant increases in residual N from the 210 kg N ha^{-1} rate on all four irrigation treatments.

There were statistically significant differences in NO_3^--N levels due to irrigation treatments on the 0 N + 20 P and 210 N + 0 P treatments in 1981, and on the 210 N + 40 P treatment in 1982. The high value on treatment I-3 on the 0 N + 20 P treatment does not seem logical. It may have resulted from pre-existing variations in soil NO_3-N levels. The higher values for the 210 N treatments on treatment I-4 are logical, since less N uptake was measured on treatment I-4 than on the other irrigation treatments.

Water Use Efficiency. Water use efficiency increased with increasing increments of N on all irrigation treatments except treatment I-4 (Table 6). On treatment I-1 the 140 kg N ha^{-1} rate was sufficient for maximum WUE, while the 70 kg N ha^{-1} rate was sufficient on the other irrigation treatments. On treatment I-4 the fertilizer treatments did not affect WUE in 1981; but in 1982, when there were trends (not significant) toward increased yields on the 210 N + 0 P and 210 N + 40 P treatments, those treatments resulted in WUE significantly higher than that of the 0 N + 20 P treatment. Since such differences did not occur in 1981 and the two fertilizer treatments did not give WUE different from the 210 N + 20 P treatment on any of the other irrigation treatments, the significant differences are concluded to have resulted from chance and probably could not be repeated.

In 1981, on adequately fertilized treatments, WUE was highest on treatment I-1 and lowest on treatment I-4, while WUEs on treatments I-2 and I-3 were similar to each other and intermediate to those on treatments I-1 and I-4. In 1982, however, efficiencies were highest on treatment I-4 and lowest on treatments I-1 and I-3, while treatment I-2 tended to be intermediate. Grain yields on the various treatments were similar in both years. The differences in WUEs on treatment I-4 between the 2 yr resulted from less water use on treatment I-4 in 1981 to 1982 than in 1980 to 1981. Less water was used, even though precipitation between planting and harvest was higher in 1981 to 1982 than in 1980 to 1981 (262 vs. 171 mm). The higher WUE in 1981 to 1982 may have been at least partially due to differences in temperatures and rainfall distribution during the two seasons. Temperatures during the grain filling and ripening periods were above normal in 1981 and below normal in 1982. Also, rainfall occurred on 21 d during May and June in 1982 and only on 8 d in 1981. The cooler, moist conditions in 1982 allowed normal grain filling and ripening on treatment I-4 and reduced the effects of stress during that period on treatment I-2. Drought conditions hastened maturity on those treatments in 1981, resulting in reduced grain and test weights and, consequently, lower WUE.

Irrigation Water Use Efficiency. Irrigation water use efficiency increased with increasing increments of applied N through 140 kg ha^{-1} on treatments I-1, I-2, and I-3 in 1981, and treatments I-1 and I-3 in 1982. On treatment I-2 in 1982, IWUE increased with N through the 70 kg N ha^{-1} rate (Table 6).

In 1981, IWUE was similar on treatments I-1 and I-2 but was reduced on treatment I-3. The lower IWUE on treatment I-3 compared to treatment I-2 resulted from yields being similar on the two treatments, with more water being applied to treatment I-3. In 1982, IWUE was about one-half that of 1981, and the only significant difference among irrigation treatments was the 70 N + 20 P fertilizer treatment, where treatment I-2 was more efficient than treatments I-1 and I-3. The low IWUE in 1982 resulted from comparatively high yields on treatment I-4 in that year.

Fertilizer × Irrigation Interaction. Fertilizer × irrigation interaction effects were present in the grain yield data, shown in Fig. 1, as well as in straw yields, N yields, and other data. Without irrigation, applied N had little effect on yield, because the soil supplied enough N for yields as high as the water supply would allow. Without applied N, N was limiting when water was applied. Both applied N and water were required for substantial yield increases from either variable. For the most efficient use of both N and water, the supply of one should be adjusted to that of the other. If irrigation is for maximum yields, fertilization should be too; but if irrigation is limited, the fertilizer supply should be limited accordingly.

CONCLUSIONS

If limited irrigation is to be used in wheat production in the Southern Great Plains, it can be used more efficiently by preventing stress during tillering and jointing than during heading and grain filling. In this study, only one irrigation was applied to prevent stress during tillering, and two were applied during heading and grain filling. With similar yields, IWUE was greater with one irrigation than with two. Admittedly, for WUE the treatment receiving the single irrigation was favored, but even if a treatment having only one irrigation during heading and grain filling had been included and IWUE had been as efficient as that on treatment I-2 of this study, irrigation to prevent stress during tillering and jointing would be more advisable than delaying irrigation until heading and grain filling. Stress during tillering and jointing limits yield potential that is not regained when stress is relieved. Thus, if stress is prevented until heading, there is still potential for maximum yields if precipitation occurs during heading and grain filling, while if plants are stressed earlier, the yield potential is lost. Rainfall records in the area show that the probability of receiving significant rainfall is much greater during May and June than during March and April (Stewart and Burnett, 1987).

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